Probing strong gravity and extreme astrophysics around black holes with Constellation-X

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Abstract

One of the primary missions of the Constellation-X observatory will be to study the structure of spacetime at the brink of black hole event horizons, as well as the behaviour of matter and energy in these extreme environments. We discuss how Constellation-X observations of broad iron line variability will facilitate these fundamental investigations.

1 Introduction

Black holes represent the ultimate victory of gravity over all other forces of nature. Einstein's general theory of relativity tells us that black holes are regions of spacetime that have been so severely warped that our notion of time itself grinds to a halt at the "event horizon", and the interior of the event horizon is in a real sense completely removed from our observable Universe.

But, what really happens at the edge of a black hole? Do physical laws that go beyond Einstein's theory start to become apparent as one approaches the brink? And how do matter and energy behave in such extreme conditions? Exploring these questions is one of the fundamental goals of NASA's Beyond Einstein program, and Constellation-X is central to that investigation.

X-ray astronomy is already realizing the promise of using black holes as probes of strong gravitational fields. Observations of Galactic Black Hole Candidates (GBHCs) with the *Rossi X-ray Timing Explorer* have revealed high-frequency quasi-periodic oscillations in the X-ray flux that, presumably, are giving us a window into the innermost regions of the accretion disks in these systems. However, the best understood strong gravity probes to date are the extremely broadened and redshifted accretion disk iron emission lines extensively studied by *ASCA* (Tanaka et al. 1995; Nandra et al. 1997) and *XMM-Newton* (Wilms et al. 2001; Fabian et al. 2002). While providing a powerful probe of the black hole spin and accretion disk structure, the current studies have fundamental limitations. Even *XMM-Newton* requires long integrations to determine broad iron line profiles — modeling of the resulting time-average line profiles reveals degeneracies between the underlying spacetime metric (incl. the black hole spin) and the accretion disk structure.

In this poster, we show how Constellation-X can take studies of broad iron lines to the next level, using observations of iron line variability to cut through these remaining degeneracies.

2 Dynamical timescale variability

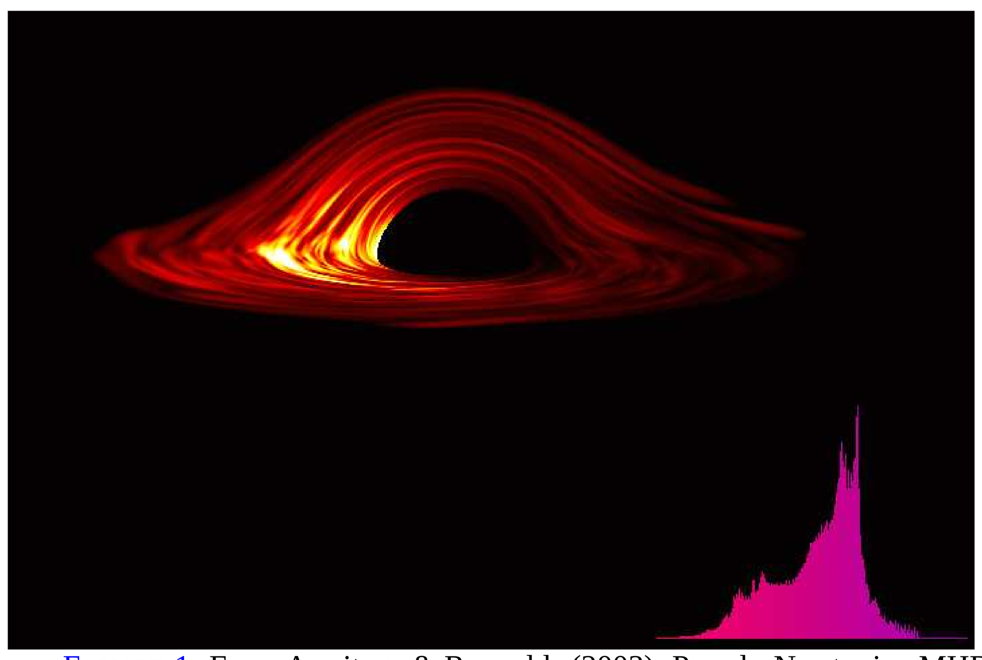

FIGURE 1: From Armitage & Reynolds (2003). Pseudo-Newtonian MHD simulation of a turbulent accretion disk which has been ray-traced through a Schwarzschild metric. Magnetic stress ($B_r B_\phi$) is used as a proxy for dissipation. The effects of light-bending and relativistic aberration are clearly visible. A simulated iron line profile is shown in the bottom right. The case of an 80° inclination is shown.

Black hole accretion is thought to proceed through a disk due to magneto-hydrodynamic (MHD) turbulence driven by the magneto-rotational instability (Balbus & Hawley 1991). This is an inherently non-axisymmetric process. If this translates into non-axisymmetric iron line emission, the broad line profile would display well-defined variability on the dynamical timescale of the inner disk due to the orbital motion of the disk.

A simple model can illustrate the promise of this approach (Armitage & Reynolds 2003). Fig. 1 shows the results of a pseudo-Newtonian MHD simulation of an accretion disk which has been ray-traced through a full Schwarzschild metric to account for the effects of light bending (using Maxwell stress as a proxy for dissipation). Fig. 2 shows the predicted iron line variability from this simulations, assuming that the local iron line emission follows our dissipation proxy. Well defined arcs are seen on the (E,t)-plane corresponding to the orbital motion of distinct "active" regions in the disk. To a good approximation, each arc traces out a test-particle orbit deep within the black hole potential. Constellation-X will be able to trace these arcs in the (E,t)-plane, allowing one to fit relativistic orbits to constrain black hole mass and spin. Even a conservative extrapolation suggests that accretion disks simulations will be sufficiently advanced to enable the non-gravitational effects (i.e., deviations from test-particular orbits) to be quantified and corrected.

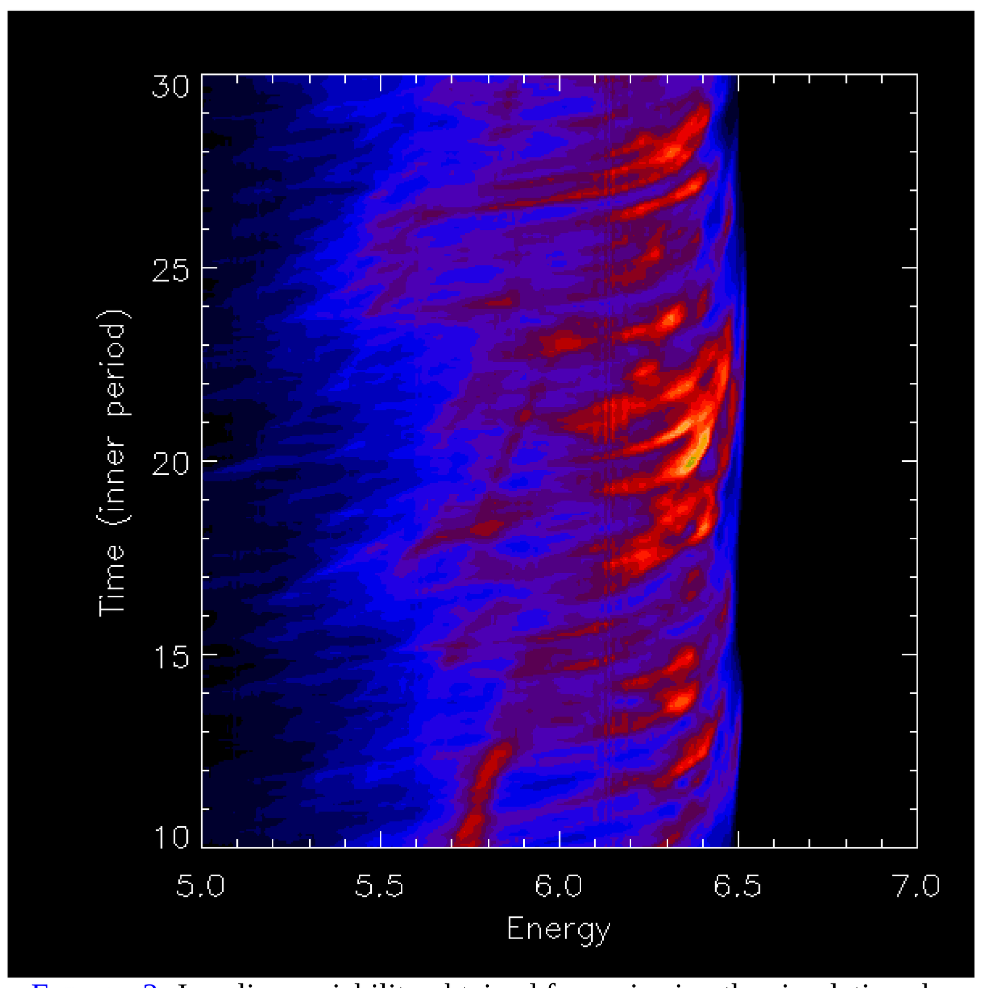

FIGURE 2: Iron line variability obtained from viewing the simulation shown in Fig. 1 at an inclination of 20°, assuming that line emissivity tracks our dissipation proxy. The arcs correspond to the orbital motion of individual active structures within the disk.

3 Light-crossing timescale variability

The hard X-ray flux from many broad iron line AGN is extremely variable. Violent flaring events in the X-ray source can lead to "echoes" of X-ray emission that sweep across the accretion disk producing iron line variability on the light-crossing timescale. Broad iron line reverberation gives a powerful window into the nature of strong gravity.

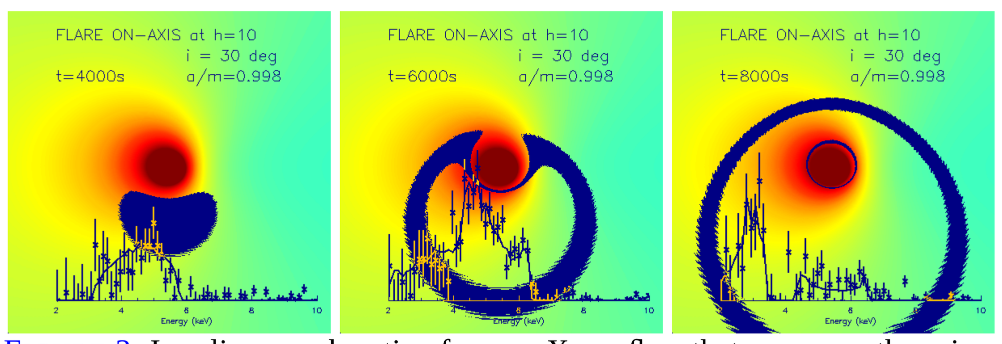

FIGURE 3: Iron line reverberation from an X-ray flare that occurs on the spin axis (at $r = 10GM/c^2$) of a rapidly-rotating black hole (Reynolds et al. 1999). The X-ray echo breaks into two branches; the normal outward-moving echo and an inward-moving echo. The inward-echo is a pure relativistic phenomenon due to the divergent gravitational redshift associated with the event horizon. Also shown is simulated Constellation-X data assuming a flux characteristic of a bright Seyfert galaxy and a black hole mass of $10^8\,M_\odot$ (Young & Reynolds 2000).

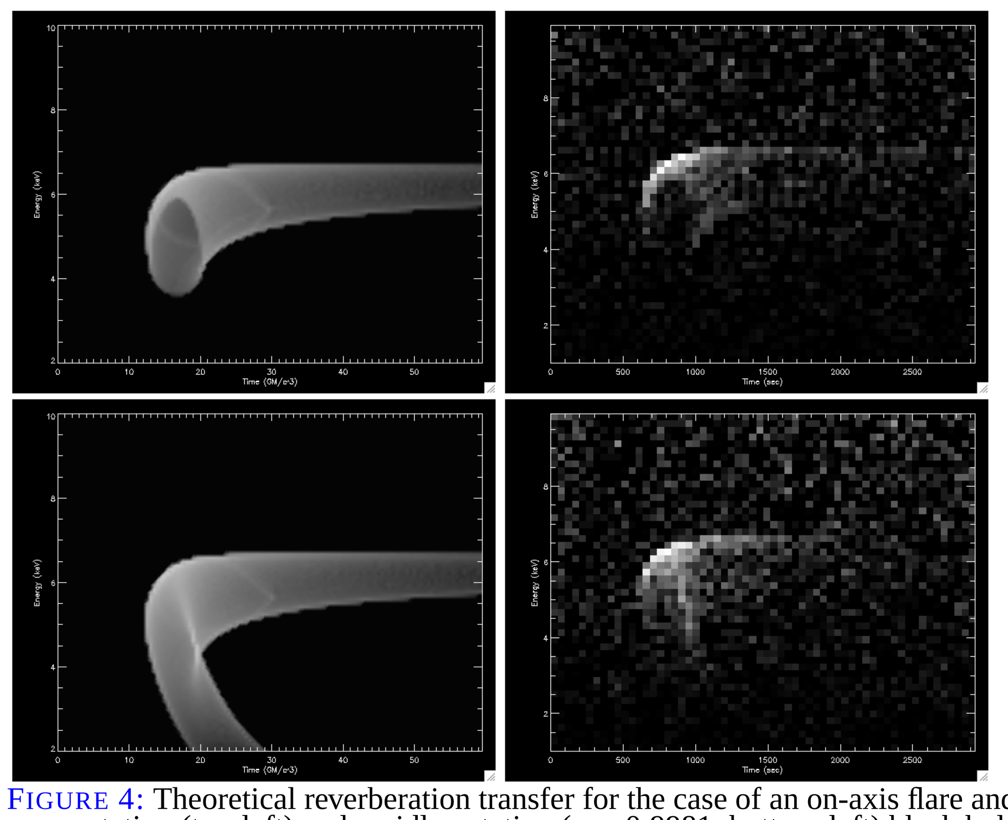

FIGURE 4: Theoretical reverberation transfer for the case of an on-axis flare and a non-rotating (top-left) and rapidly-rotating ($a = 0.9981$; bottom-left) black hole. Also shown are simulated observed reverberation transfer functions assuming the source has a flux characteristic of MCG–6-30-15 and a black hole mass of $10^7\,M_\odot$ (a reasonable estimate for MCG–6-30-15; Reynolds 2000).

Simulations of broad iron line reverberation (Reynolds et al. 1999; Young & Reynolds 2000) show that, in addition to the usual outward-bound light echo, extreme gravitational redshifts close to the black hole produce an *inward*-bound light echo (Fig. 3). This inward-bound echo produces a distinct feature in the iron line reverberation signature, a bump that rapidly redshifts down the spectrum. Through this spectral feature we are probing close to the very edge of the event horizon; its properties are a sensitive function of the spacetime geometry there.

An obvious candidate for study by Constellation-X is the broad iron line AGN MCG–6-30-15. Fig. 4 shows both theoretical and simulated Constellation-X transfer functions for MCG–6-30-15. Visual examination shows that the transfer function can be reconstructed well. Furthermore, summing the constraints from many flares will vastly improve the power of these observations to diagnose the detailed space-time structure of the black hole.

4 Detectability

While targeted Constellation-X simulations of the kind shown above for iron line reverberation are required, it is instructive to consider more general detectability constraints. In Fig. 5, we use the baseline Constellation-X effective area curve to deduce the time required to obtain a 3σ detection of a redshifted iron line for parameters typical of a bright Seyfert galaxy. Also shown are regions indicating where we expect to find the dynamical timescale effects of Section 2 (yellow ellipse) and the reverberation effects of Section 3 (red ellipse). One can see that the dynamical timescale effects are straightforwardly detectable by Constellation-X whereas the reverberation effects are clearly more challenging. This calculation also demonstrates that the effective area in the 3–5 keV band is even more crucial than the area in the so-called iron-K band (6–7 keV); it is in this lower band that we expect to find the it redshifted features.

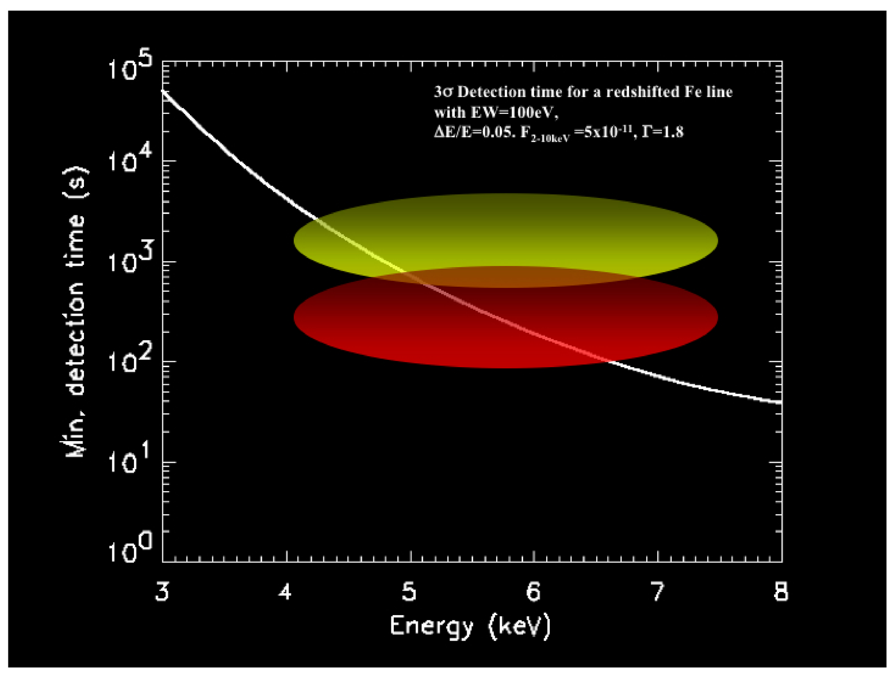

FIGURE 5: Time taken to furnish a 3-σ detection of a redshifted 6.4 keV iron line (as a function of the observed line energy) which has a (rest-frame) equivalent width of 100eV and a fractional width of 0.05, given a 2–10 keV source flux characteristic of one of a bright Seyfert galaxy ($5\times10^{-11}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$). The yellow ellipse shows the time/energy range where dynamical/orbital line variability is expected. The red ellipse shows the range for reverberation effects.

5 Conclusions

Constellation-X will give us a powerful window into the underlying spacetime geometry at the very edge of black hole event horizons, as well as the behaviour of matter in these extreme environments. Broad iron line variability will allow us to watch matter as it executes its final few orbits around the black hole, and track echoes of X-ray light right up to the brink.

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